

Advances in Discrete Fracture Network Modeling

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Abstract

This paper describes recent advances in discrete fracture network (DFN) modeling and analysis. These advances represent a significant convergence between DFN and EPM methods for flow, combined with significant increases in geological realism, and more appropriate solute transport conceptual models.

Introduction

Since its introduction in the late 1970's, considerable controversy has raged in the hydrogeologic community over the value of discrete fracture network (DFN) approach, and particularly about the merits of the DFN approach as compared to the stochastic continuum approach. Much of this controversy has been related to the fundamental concept of the representative elementary volume (REV) which underpins all continuum approaches (Bear, 1972).

According to the REV concept, there exists a scale at which individual heterogeneities and discrete features can be ignored, due to a process of averaging to produce an effective continuum medium. The fundamental motivation of discrete fracture network (DFN) modeling is the recognition that at every scale, groundwater transport in fractured and carbonate rocks tends to be dominated by a limited number of discrete pathways formed by fractures, karts, and other discrete features. The DFN approach can thus be defined as *“analysis and modeling which explicitly incorporates the geometry and properties of discrete features as a central component controlling flow and transport.”*

Discrete Fracture Network related research carried out over the past twenty years has focused on identifying those individual discrete features and karts which provide discrete connections which carry the most important portion of flow. The task of hydrogeology then becomes to characterize these individual pathways, rather than the average or REV properties of the medium. To achieve this, it is necessary to understand the geometry and properties of the discrete fractures and karts which form these pathways.

The development of this discrete feature conceptual model is the essence of the DFN approach. The DFN approach provides the three dimensional framework of discrete features which concentrate flow and transport, and also the flow barriers such as faults and argillaceous layers which provide partial or complete seals. This DFN conceptual model can be referred to as a discrete feature “hydrostructural model” (Winberg et al., 2003).

Once the DFN hydrostructural model has been implemented, and the discrete features of importance are known deterministically, or at least stochastically, the DFN can then be solved to address the specific flow and transport engineering issues of concern.

This paper highlights several trends in DFN modeling including:

- Convergence of DFN and Continuum Methods,
- Increasing Geologic Realism, and
- Multiple Immobile Zone Transport

Convergence of DFN and Continuum Methods

DFN analysis is fundamentally about the development of an appropriate hydrostructural model which considers the role of known and unknown discrete features in controlling flow and transport. As such, DFN analysis is essential for conventional continuum approaches using volume elements as it is for flow and transport models built on pipe or plate discrete feature elements. If you don't know the nature of discrete feature transport pathways or flow barriers, you can't carry out conventional continuum modeling any more than you can DFN flow and transport modeling.

A recent example of this is shown in Figures 1, 2, and 3. Figure 1 illustrates the hydrostructural model developed to describe a 200 m scale block of Äspö granite within the Äspö hard rock laboratory. Figures 2 and 3 illustrate DFN and EPM implementations of this model. The EPM implementation of the model (Gomez-Hernandez et al., 2003) fits the definition of a DFN model, since it explicitly considers the discrete features

identified within the discrete feature hydrostructural model. However, the EPM implementation uses volume elements at the scale of 5 m, which is coarse considering the 2 cm in total thickness of the fractures being modeled.

Comparison of Figures 2 and 3 demonstrates that the debate over EPM vs. DFN is no longer about the value of the DFN hydrostructural approach, but only about the most efficient implementation. Both EPM and DFN models were built on a common DFN hydrostructural model, developed using DFN analysis techniques.

During recent years, this has led increasingly to the development of hybrid DFN/EPM models such as ConnectFlow (Serc0, 2004) and FracWorks XP (Dershowitz et al., 2004). There are three types of integration for DFN/EPM models.

- Layered DFN/EPM Models,
- EPM Implementation of DFN Hydrostructural Models, and
- Nested DFN/EPM Models.

Layered DFN/EPM Models

In many geological environments, heterogeneously connected karstic or fractured rocks occur within stratigraphic columns containing units best represented by continuum elements. Layered DFN/EPM Models meet this by incorporating both EPM volume elements, and DFN (pipe or plate) elements. Figure 4 illustrates a layered DFN/EPM model, with the EPM representing primarily sandstone layers, and the DFN representing fractured granite. The advantage of this approach is that it is able to more accurately model the response of the groundwater table and shallow wells using continuum EPM elements, while still using the DFN for evaluating connectivity between wells in the fractured granite.

The key to implementation of the layered DFN/EPM approach is the linkage between DFN nodes, which occur at the intersections between and edges of polygonal fracture elements, and EPM nodes, which occur at the corners of tetrahedral or hexahedral volumes.

In general, the DFN elements and EPM elements are on different scales such that there may be many DFN nodes corresponding to a single EPM node, or vis-versa. The linkage between DFN and EPM nodes is achieved by recognizing this difference in discretizations, and providing for a node based linkage. This type of linkage is illustrated in Figure 5. In this example, DFN nodes within a distance d from any EPM node are linked to the closest EPM node. This linkage can be achieved by setting the linked EPM and DFN nodes to the same head value, or by placing a pipe element of specified transmissivity between the nodes, if there is some special material at the DFN/EPM interface.

EPM Implementation of DFN Hydrostructural Models

Approaches for implementation of DFN hydrostructural models using EPM technologies include

- Explicit modeling of a key faults and fractures,
- Geostatistical simulation of faults and fractures, and
- Oda Tensor approaches.

EPM models have always been able to represent a limited number of faults and fractures explicitly using the same volumetric elements that are used to represent other geologic materials. Where these few discrete features carry the vast majority of flow and transport, these EPM models could be considered a fairly straightforward DFN hydrostructural model implementation. In examples reviewed for this paper, examples were found where over 95% of the flow occurred in the explicitly modeled discrete features, such that the EPM model was functionally identical to a DFN.

EPM models of discrete features have been implemented using finite element (Figure 6), finite difference (Figure 7), and finite volume methods. Of these, the finite element method is attractive since the grid can be adjusted to conform to the fracture geometry. In contrast, the finite difference method generally requires a

stairstepped approximation. The finite volume method is frequently significantly less computationally efficient than either the finite element or finite difference methods, but has advantages for modeling coupled processes.

Geostatistical Simulation of Faults and Fractures

Traditional geostatistical simulation derives variograms from the spatial pattern of hydraulic properties, and then attempts to reproduce this pattern by kriging from these variograms. Given the complex, three dimensional nature of faults and fractures, this method is unlikely to be able to regenerate the pattern of semi-planar discrete features.

During the past ten years, advances in geostatistical modeling has made it possible to implement geostatistical models which reproduce and also enhance DFN hydrostructural models.

- a) indicator kriging – cells can be marked based on the occurrence of fractures or flow barrier faults, and the geostatistically derived property fields can be adjusted accordingly. This produces fields which correspond to the location and properties of the discrete features.
- b) co-kriging – cell hydraulic properties can be adjusted based on a combination of both the hydraulic test results which provide permeability and storativity, and the geophysical fields which are indicators for the location of faults.
- c) numerical inversion – geostatistical EPM model cell hydraulic properties can be optimized by a combined inversion of the underlying DFN hydrostructural model, geophysical data, and hydraulic data.

The effectiveness of the integrated hydrostructural, hydrologic, and geophysical numerical inversion approach is illustrated in Figure 6 (Will et al., 2003).

Oda Tensor Approaches

The Oda (1985) method for calculating EPM properties from DFN fractures is now twenty years old, and has been re-derived with variations many times. The advantage of the Oda approach is that it can obtain EPM properties for grid cells based directly on the geometry and properties of the fractures within those cells.

The Oda approach begins by generating the full, three dimensional DFN. While DFN flow and transport modeling is limited to on the order of 10^4 to 10^5 fractures by computational constraints, the Oda approach can be applied to patterns of 10^7 or more fractures. The Oda approach overlays an EPM grid on the fractures, and derives EPM properties for each grid cell based on the DFN contained in that cell.

The orientation of fractures in each grid cell is expressed as a unit normal vector n . Integrating the fractures over all of the unit normals N , Oda obtained the mass moment of inertia of fracture normals distributed over a unit sphere:

$$N = \int_{\frac{\Omega}{2}} n_i n_j E(n) d\Omega \tag{1}$$

where:

- N = number of fractures in Ω .
- n_i, n_j = the components of a unit normal to the fracture n
- $E(n)$ = probability density function that describes the number of fractures whose unit vectors n are oriented within a small solid angle $d\Omega$
- $\tilde{\Omega}$ = entire solid angle corresponding to the surface of a unit sphere

For a specific grid cell with known fracture areas, A_k , and transmissivities, T_k , obtained from the DFN model, an empirical fracture tensor can be calculated by adding the individual fractures weighted by their area and transmissivity:

$$F_{ij} = \frac{1}{V} \sum_{k=1}^N f_k A_k T_k n_{ik} n_{jk} \quad (2)$$

where:

F_{ij}	=	fracture tensor
V	=	grid cell volume
N	=	total number of fractures in grid cell
f_k	=	percolation factor for fracture k (generally assumed to equal 1)
A_k	=	area of fracture k
T_k	=	transmissivity of fracture k
n_{ik}, n_{jk}	=	the components of a unit normal to the fracture k

Oda's permeability tensor is derived from F_{ij} by assuming that F_{ij} expresses fracture flow as a vector along the fracture's unit normal. Assuming that fractures are impermeable in a direction parallel to their unit normal, F_{ij} must be rotated into the planes of permeability

$$k_{ij} = \frac{1}{12} (F_{kk} \delta_{ij} - F_{ij}) \quad (3)$$

where:

k_{ij}	=	permeability tensor
F_{ij}	=	fracture tensor
δ_{ij}	=	Kronecker delta

The Oda approximation derives an equivalent permeability tensor, according to a specific grid. This tensor can also be derived by using a numerical permeameter, in which a boundary condition is applied to the edges of the grid cell (see e.g., Long, 1984). At the extreme of fine discretization (mm scale grid cells), the Oda approximation reproduces the underlying discrete fracture hydrostructural model, both for flow and for transport. However, at the practical and much coarser discretizations of tens or hundreds of meters, the Oda approximation produces results which are less accurate.

The Oda tensor approach thus represents a balance between the accuracy of directly modeling each of the structures in the hydrostructural model, against the computational efficiency of coarser numerical model discretizations.

Nested EPM/DFN Models

The inherent compromise of using EPM models to represent DFN hydrostructural models can be reduced through the recent development of nested EPM/DFN Models. These models combine the use of DFN elements in the locations where fracture geometry is of most concern, such as at intersections with boreholes and tunnels, with EPM elements at less sensitive locations.

Figure 9 illustrates a nested EPM/DFN model. This model utilizes a coarse Oda based EPM grid for most of the model, while maintaining a direct implementation of the DFN hydrostructural model using DFN elements in the direct vicinity of the boreholes of interest.

The key to the implementation of Nested EPM/DFN models is the same as for layered EPM/DFN models, i.e., the linkage between the EPM and DFN elements, both for flow and for transport. The approach described above for layered EPM/DFN models has also been used successfully for nested EPM/DFN models.

Advances in Geological Realism

Discrete fracture network hydrostructural models are implemented by integration of

- geology
- geophysics, and
- hydrogeology

Recent advances in geophysics such as 3D VSP and AVO/AVAZ have made it possible to develop DFN hydrostructural models with explicitly incorporate the 3D geometry of structures greater than on the order of 100 m (Parney and La Pointe, 2002). This increasingly explicit information about fault geometry perhaps surprisingly increases the need for geologically and hydrologically based methods to a) derive the properties of those identified structures, and b) extrapolate from the seismic scale structures to the sub-seismic features.

In sites where geophysical characterization of structures is either economically or technically infeasible, geological and hydrogeological methods are also necessary for deriving the location and properties of both seismic and sub-seismic structures.

Below, we present three key recent advances in the geologic realism of DFN hydrostructural models:

- DFN Fault Models
- Carbonate Solution Features
- Geocellular and Bootstrap Models

DFN Fault Models

Figure 10 (after Caine, 1999) presents a schematic view of the internal structure of faults. Faults generally combine conductive and flow barrier features – a flow barrier at the fault core, combined with conductive fractures, particularly in the fault “damage zone”. Recent advances in DFN modeling provide approaches for implementing the full range of conductive, flow barrier, and partially sealing fault behaviors:

- Purely conductive faults can generally be represented as a planar or tessellated non-planar discrete feature. The variability within the fault can be represented by applying varying transmissivities to the elements defining the fault,
- Purely flow barrier faults can be represented by truncating the fractures intersecting at their fault intersection, or reducing fracture transmissivity in the vicinity of the fault intersection (Figure 11),
- Faults flowing primary in the footwall and hangingwall damage zones can be modeled by generating special fracture sets for these regions, or by representing this transmissivity within the fault surface itself, and
- Partially sealing faults can be represented by reducing the transmissivity of fractures where they connect to or pass through the fault.

These fault barrier models are an essential aspect of an increasing percentage of DFN modeling, as an increasing proportion of sites show evidence of hydraulic compartmentalization. Figure 12 illustrates an example of hydraulic compartmentalization at the “Block Scale” experiment in Sweden. Despite a strong hydraulic gradient toward the northeast due to the presence of unlined tunnels, the salinity indicates the presence of a NNW oriented flow barrier compartmentalizing the system into saline and fresh groundwater regimes.

DFN Carbonate Solution Feature Models

While some fractured rocks can be treated as single porosity materials, carbonate rocks are frequently three porosity systems, combining a significant matrix permeability with fractures and solution features such as vugs and solution enhanced discrete pathways. These features are particularly difficult to model with EPM approaches. DFN approaches for simulating carbonate solution features include the following:

Vugs: Vugs are solution features which can range in size from millimeters to tens of meters, with on the order of 100% porosity. Within DFN models, vugs can be modeled as three dimensional discrete features using either

volume element or as a storage interaction term in the approximate dual porosity approach. Figure 13 illustrates an approach for modeling vugs as storage terms interacting with fractures. In this approach, the storage in the vug interacts with the fracture through a 1-D interaction term.

Wormhole Channels: Solution enhanced fracture intersections are major form of transport pathway in fractured carbonates. These channels frequently have apertures 10 to 50 times larger than those of the intersecting fractures, such that the channel itself has a transmissivity 10^3 to 10^5 that of the fractures (assuming the cubic law applies). This can now be implemented in DFN models by adding pipe elements at karst enhanced fracture intersections. The extra storage and transmissivity of the wormhole channels can then be represented by a separate parameter. The geometry of the wormhole channels can then be defined by a geological simulation process reflecting the geologists conception of solution evolution.

Karstic Porosity on Fracture Planes: One of the key features of karstic carbonates is that certain portions of fracture planes have dramatically increased transmissivity and storage due to local solution enhancement of the fracture aperture. This may be part of a continuous pathway (as in wormholes), or it may be a local effect. For example, at the Yates Carbonate Oil Reservoir in Texas, vuggy areas on fracture plan account for most of the locations at which oil flows freely to the production wells (Wadleigh, 1998).

The karstic porosity on fracture planes can be modeled by tessellating the fracture surfaces, and applying the appropriate spatial pattern of karstic porosity to the planes. The pattern of karst porosity can be described by geostatistical or fractal methods, or on a geological basis if there is a geological theory for the spatial distribution of karstic porosity (Figure 14).

In general, the karstic porosity on the fracture plan is described by three parameters – the karsted percentage of the fracture plane area (“karstic persistence”) , the aperture distribution for the karsted regions, and the spatial pattern (e.g., range or correlation length for a geostatistical field).

Geocellular and Bootstrap Models

Fractured rock DFN hydrostructural models covering areas of more than about 1 km² generally have a spatial variability in the fracture pattern. The orientation, size, and intensity of fracturing tend to vary across the site, such that statistically homogeneous models are inadequate. The need for such models has been filled over the past five years through the development of geocellular and bootstrap models.

Geocellular models fill the entire 3D space with information extrapolated from geology, geophysics, and hydrogeologic. This information is commonly stored in Geomatic/GIS systems such as for example ArcInfo (ESRI, 2004), Petrel (Schlumberger, 2004), EarthVision (Dynamic Graphics, 2004), or StrataModel (Landmark, 2004). In these systems, the rock volume is discretized to volumetric cells, and each cell is linked to appropriate properties. In a geocellular DFN model, the fractures and faults, and their properties are generated directly from that cell-based information. For example, at the Yates field, fracture intensity was directly tied to shale content. The geocellular DFN model therefore generated fracture intensity P_{32} (m²/m³) at every location based on the relative shale content.

Another application of the geocellular approach is in generating 3D DFN hydrostructural models based on an interpreted 3D stress or strain field. In this approach, the geologic or rock mechanics analysis interprets the present or recent stress or strain field throughout the rock mass. This field may be based on, for example, stress cell measurements, or a palinspastic reconstruction of the strain history (La Pointe et al., 2003). In either case, the geocellular grid then contains a stress or strain tensor, and the fracture orientation, intensity, and transmissivity can be generated at each location in the rock contingent on the local tensor information. An example stress tensor grid based DFN model is shown in Figure 15.

Bootstrap models start with know values at specific locations (generally geophysical measurements or boreholes), and use this information directly to extrapolate the three dimensional population, without creating an intermediate synthetic geocellular field. The bootstrap algorithm is summarized as follows. When generating a fracture at a specific location, the model looks for data which is relevant, and ranks that data by its relative relevance. For example, for generating a fracture orientation, the most relevant data would be near by, in the same stratigraphic unit, and on the same side of any significant structural feature such as a fault. The fracture orientation at that location would then be generating by choosing a single measured value from the table of relevant measurements, with a probability weighted by relevance. Once a particular value was chosen,

a small dispersion factor would be applied to account for the stochastic and spatial variability. This process is illustrated in Figure 16.

The advantage of the bootstrap approach is that it directly utilizes available data, rather than an interpolated field, as in the geocellular approach. This works well when there is good spatial coverage for data, or where there is no appropriate method for populating a geocellular field.

Multiple Immobile Zone Transport

The key advance in fractured rock transport analysis over the past ten years is the gradual realization of the importance of the interaction between mobile and immobile zones in fractured rock. The conventional EPM approach assumes a single, mobile (advective) porosity, with retardation occurring through sorption to grain surfaces within that porosity. In fractured rock, in situ experiments such as those at Äspö, Sweden (Winberg et al., 2003) have demonstrated that the transport in fractured rock is strongly dependent on the interaction between advective transport in fractures, and the storage of solutes in immobile zones. These immobile zones include a) gouge, breccia, cataclasite, calcite, and mylonite in the fracture itself, b) fracture coatings, c) the higher porosity altered/damaged zone surrounding many fractures, and d) intact rock (Figure 17). The geometry and properties of these immobile zones are characterized as the “microstructural model” for the fractures, and are as important as the DFN hydrostructural model discussed above for many transport analysis applications.

Four basic types of transport approaches have been developed to describe transport in fractured rock with multiple immobile zones:

Diffusive Exchange (Sudicky and McLaren, 1992). This approach implements the conventional advection-dispersion-diffusion equation in the Laplace domain. In this approach, the exchange between mobile and immobile zones is exclusively due to a diffusive process expressed by the concentration gradient between the advective and immobile zones. Multiple immobile zones can be defined both in parallel and in series, allowing explicit use of measured values for each immobile zone.

Multirate Diffusion (Fleming and Haggerty, 2001, Cvetkovic et al., 1999). Rather than depending on a characterization of the properties of each of the immobile zones listed above, the multirate approach assumes a continuous distribution of immobile zone porosities, generally defined by a Pareto or Powerlaw distribution. This assumption allows a single exchange term between the mobile and immobile zones, while recognizing the importance of the different characteristics of different immobile zones. In the Cvetkovic et al (1999) implementation “LaSAR”, advection and diffusion are described by a lumped immobile zone retention parameter κ and by the distribution of inverse aperture weighted advective velocity β .

CTRW Continuous Time Random Walk (Berkowitz et al., 2000) treats both diffusion and Gaussian dispersion as special cases of multi-rate advection, and can reproduce both diffusive and Gaussian transport on the basis of a single parameter β , the power for the assumed powerlaw (Pareto) distribution of velocity.

Advective exchange (AX) (Miller, 1996) assumes that the process of exchange between mobile and immobile zones occurs at a fixed rate of exchange per meter of advection, rather than at a rate proportional to differences in concentration. The approach is based on two parameters: β , the number of advective exchanges per meter, and f_{imm} , the ratio of the immobile zone volume to the mobile zone volume.

The above approaches have several common features of interest to practical applications

- They all depend on accurate characterization of fracture immobile porosities through an appropriate microstructural model
- They all recognize explicitly that transport is occurring on discrete features, and assume that the advective velocity within fractures (rather than the effective EPM velocity) is the relevant parameter
- They all have been used successfully in predictive simulations of solute transport at 10 to 50 m scales
- They generally use β as a key universal parameter!

Conclusions

This paper has attempted to highlight recent advances in the discrete fracture network approach to flow and transport modeling for fractured and karstic rock. Major advances have been made in the development and implementation of hydrostructural models for fracture geometry, and microstructural models, for the immobile zones influencing solute transport. These advances have made it possible to build more accurate three dimensional hydrogeologic models, and to better analyse both flow and transport processes.

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Biographical Sketch

William Dershowitz, Paul Lapointe, and Thomas Doe are the senior staff of the FracMan Technology Group in Golder Associates' Redmond WA office. The authors have an aggregate of over 75 years of experience in characterizing and simulating flow in fracture networks. The signature product of the FracMan Technology group is the **FracMan**[®] family of DFN modeling and data analysis software. These methods have been used for fractured rock research for radioactive waste research in underground laboratories in Sweden, Japan, Switzerland, and France as well as practical applications for petroleum, solid waste, and civil engineering.

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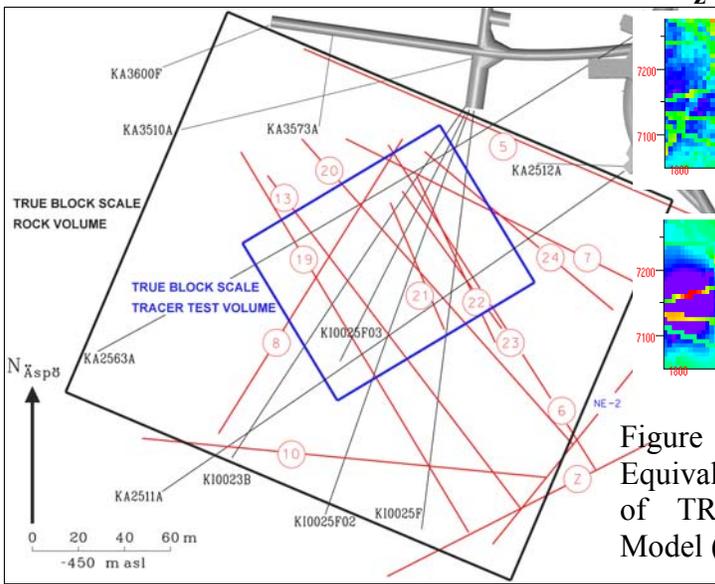


Figure 1. Numbered Structures Comprising the Hydrostructural Model for the TRUE Block Scale Experiment (after Poteri et al., 2003)

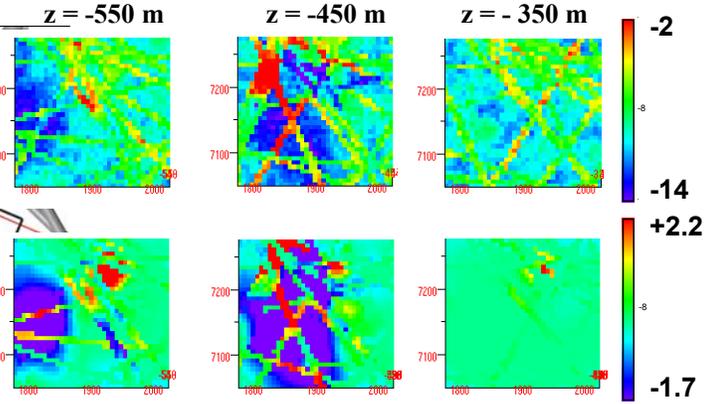


Figure 3. Gomez-Hernandez (2002) Equivalent Porous Medium Implementation of TRUE Block Scale Hydrostructural Model (after Poteri et al, 2003)

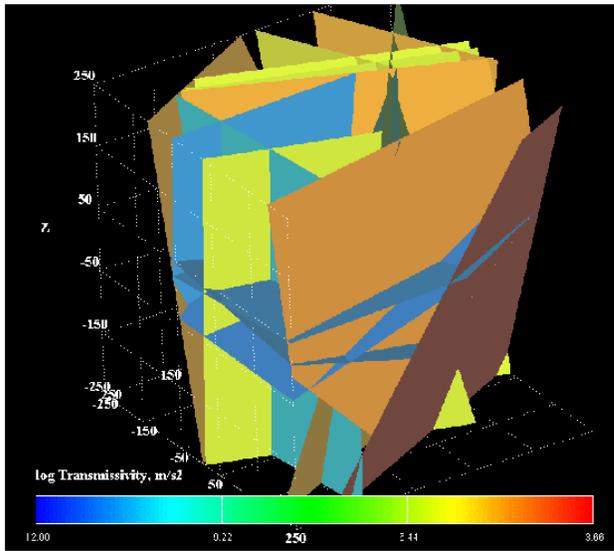


Figure 2. Dershowitz et al (2002) Discrete Fracture Network Implementation of TRUE Block Scale Hydrostructural Model (after Poteri et al, 2003)

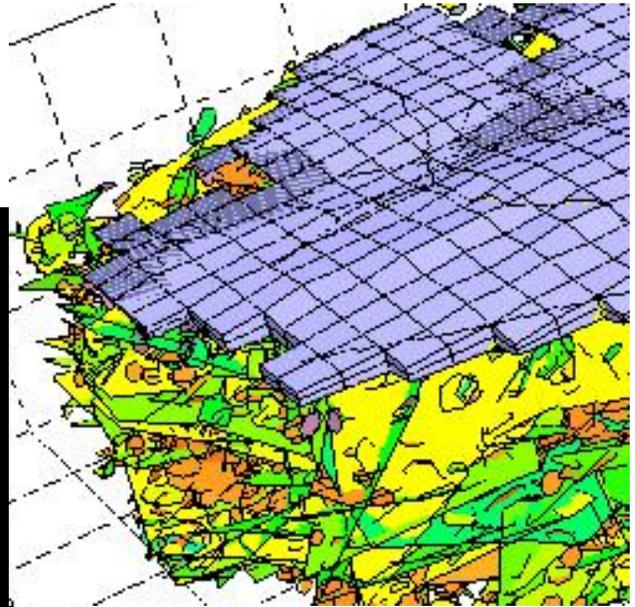


Figure 4. Layered EPM/DFN Model

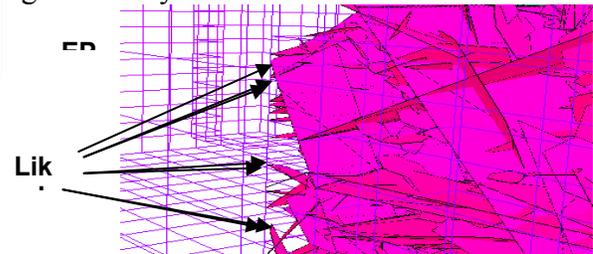


Figure 5. Linking EPM and DFN Nodes

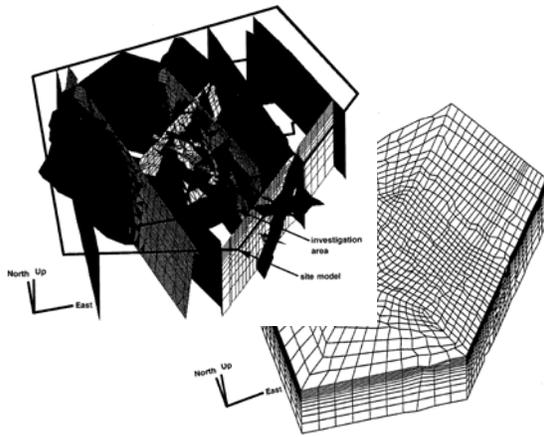


Figure 6 Finite Element Implementation of DFN Hydrostructural Model (Taivassalo and Meszaros, 1994)

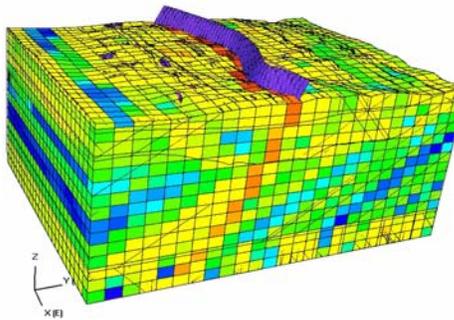


Figure 7. Finite Difference EPM Implementation of DFN Hydrostructural Model

adjusted the DFN hydrostructural model, then transformed this model to an EPM using the Oda tensor approach (after Will et al., 2003)

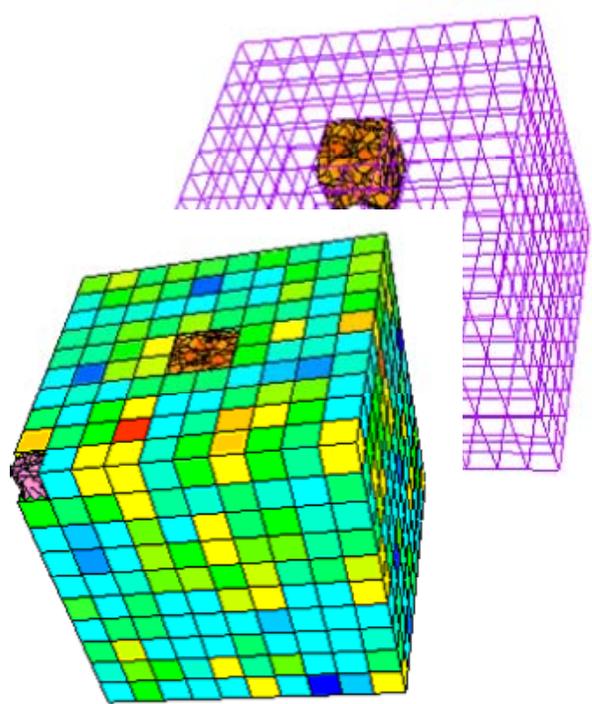


Figure 9. Nested DFN/EPM Model

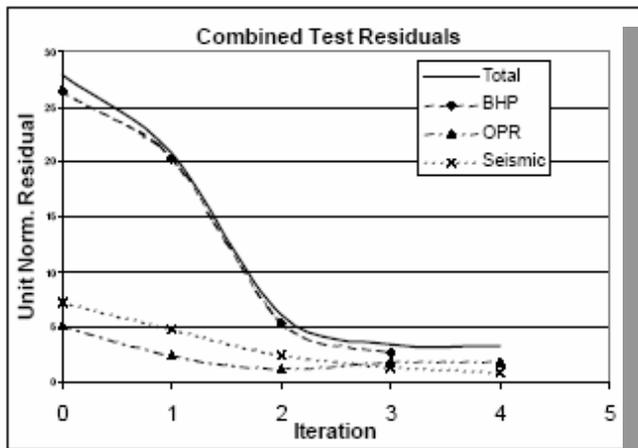


Figure 8. Combined Inversion of DFN and EPM Models Using geophysical and hydraulic data. BHP and OPR and borehole pressure and simulated oil production rate, respectively. The inversion simultaneously

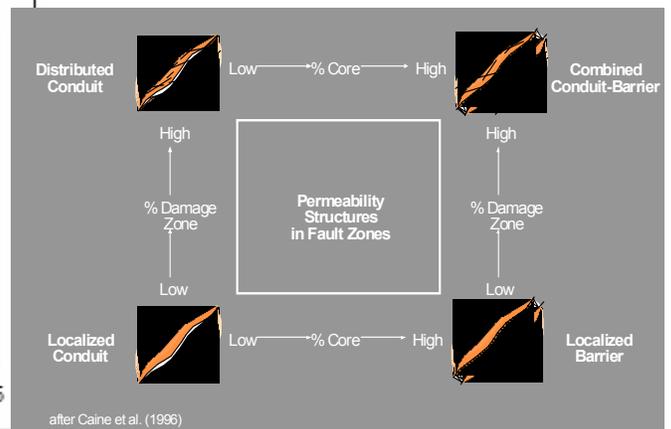


Figure 10. Conceptual Models for Faults in DFN Hydrostructural Models (after Caine, 1999)

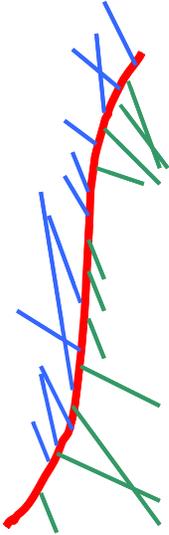


Figure 11. Flow Barrier Fault implementation in DFN Model. Hangingwall and Footwall fractures both terminate against surface representing fault. Conductivity across fault is therefore controlled by the permeability of the fault plane itself.

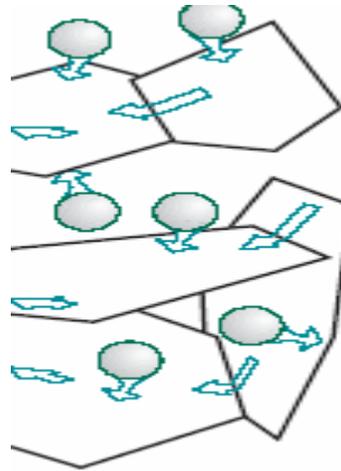


Figure 12. Representation of Vug Storage Orosities in DFN Models

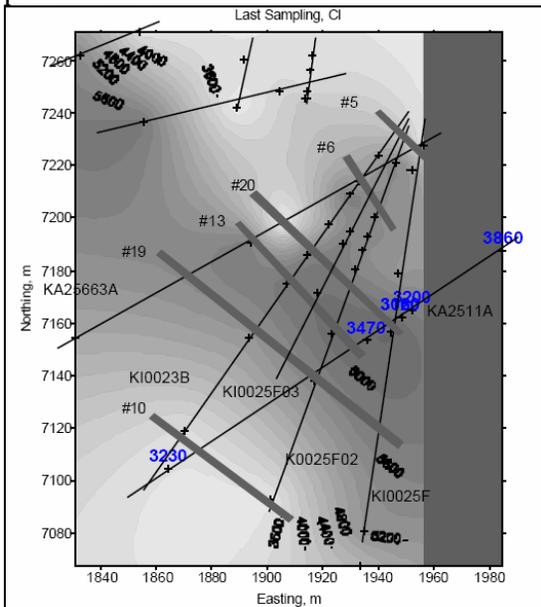


Figure 12. Geochemical Evidence of Hydraulic Compartmentalization at Äspö TRUE Block Scale (after Doe et al., 2002). Contours should compartmentalized concentration of Cl⁻, despite strong NE gradient .

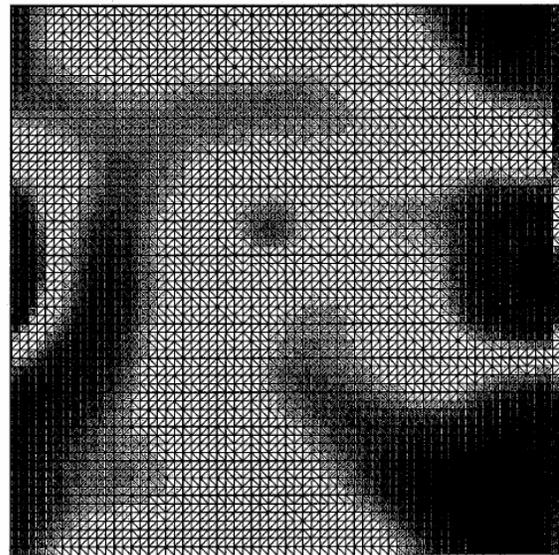


Figure 14. Pattern of Karst Porosity on Fracture Plane

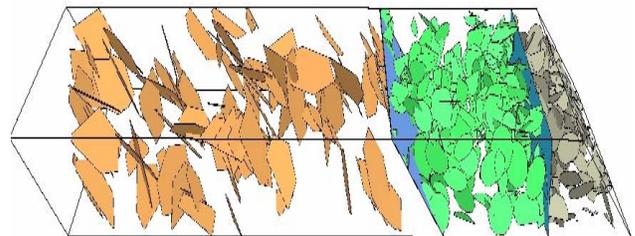


Figure 15. Stress Model Based DFN

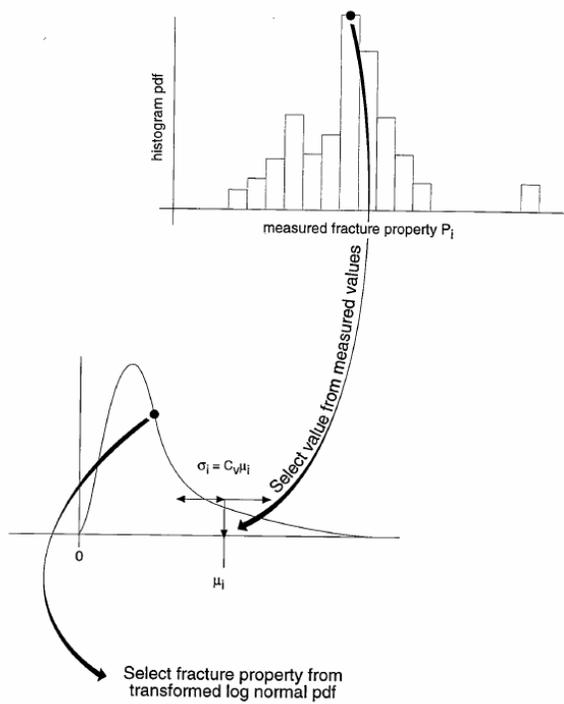


Figure 16. Bootstrap DFN Model

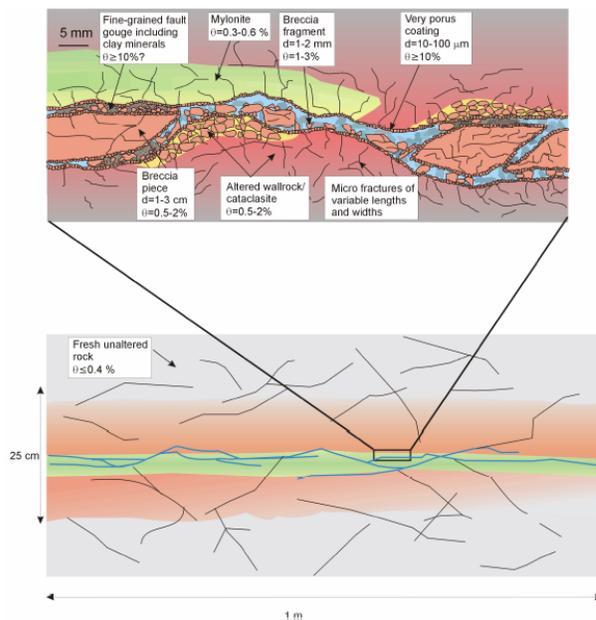


Figure 17. Immobile Zones (after Winberg et al, 2003)